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ADVANCED SENSOR AND PACKAGING TECHNOLOGIES FOR INTELLIGENT ADAPTIVE ENGINE CONTROLS (PREPRINT)

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14. ABSTRACT
The development of a pressure/temperature multi-sensor based on a combination of micro-electromechanical systems (MEMS) sensor technology, novel ceramic materials, high-temperature electronics, and advanced harsh-environment electronics packaging is discussed. The pressure/temperature multi-sensor enables unprecedented monitoring of propulsion, energy generation, and industrial systems. A multi-sensor approach will reduce control system weight and wiring complexity, design time, and cost. Multi-sensor control strategies do better than the single-sensor strategy on the basis of both to raise the accuracy and fault tolerance ability effectively. The resulting sensors and packaging can be manufactured at low cost and operate in corrosive environments, while measuring temperatures up to 2,552 °F (1,400 °C) with simultaneous pressure measurements up to 1,000 psi. The combination of a high-temperature, high-pressure-ratio compressor system, and adaptive engine technologies enables high thrust and efficiency.

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Advanced Sensor and Packaging Technologies for Intelligent Adaptive Engine Controls

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Keywords: Smart Sensor, Dynamic Sensor, Adaptive Engine Control, Distributed Engine Control, HT Electronics, Electronics Packaging

Abstract: The development of a pressure/temperature multi-sensor based on a combination of micro-electromechanical systems (MEMS) sensor technology, novel ceramic materials, high temperature electronics, and advanced harsh environment electronics packaging is discussed. The pressure/temperature multi-sensor enables unprecedented monitoring of propulsion, energy generation and industrial systems. Multi-sensor approach will reduce control system weight and wiring complexity, design time and cost. Multi-sensor control strategies do better than the single-sensor strategy on the basis of both to raise the accuracy and fault tolerance ability effectively. The resulting sensors and packaging can be manufactured at low cost and operate in corrosive environments, while measuring temperatures up to 2552°F (1400°C) with simultaneous pressure measurements up to 1000 psi. The combination of a high-temperature, high pressure-ratio compressor system and adaptive engine technologies enable high thrust and efficiency. The multi-sensor approach will potentially provide an opportunity for sensor level fusion where multiple sensors measuring correlated parameters. In-situ deployment of these sensors enables advanced compressor and combustor control schemes for prognostics and active control that facilitate environmentally responsible aviation. Current efforts include: combining the sensor technology with high temperature electronics to produce 'smart' sensors for distributed engine controls, capacitive transducer elements with increased dynamic bandwidth, and advanced sensor packaging technologies. The key technologies of intelligent engines are active controls, advanced diagnostics, and prognostics which require smart sensors. The ability to sense the current engine operating condition and state and react with adaptive controls requires robust sensors. It is essential that these sensors are tested in a relevance environment. In this paper, some testing will be reported. Additional engine testing is planned through the NASA Vehicle Integrated Propulsion Research (VIPR) and Air Force Small Component and Engine Structural Assessment Research (S-CAESAR) Engine Demonstrator programs.

Introduction

Former Defense Secretary Panetta linked energy and the environment to national security [1] and the Air Force is the largest consumer of fuel in the DoD [2]. Commercial airlines are also concerned with reducing fuel consumption and costs [3].

Active combustion control improves specific fuel consumption while reducing the emissions of oxides of nitrogen [4]. Dynamic pressure sensors are a key enabling technology for active combustion control, but current dynamic pressure sensors require liquid cooling to survive in situ compressor discharge (P3) temperatures which increases weight and cost [5].

As military and commercial turbine engine users have sought to increase performance and reduce costs, Distributed Engine Control (DEC) has also been identified as an important architectural paradigm shift to achieve increase flexibility, scalability, fault tolerance and performance while reducing weight, lifecycle costs and obsolescence risk [6]. 'Smart' sensors are seen as a key enabler for DEC [7].

As smart sensors, actuators and control elements are distributed around the engine, the need for robust, high temperature capable electronics and electronics packaging becomes critical [8]. While the temperature capability for electronics varies with engine location the need for a consistent communication interface does not. Therefore, the development of a communication standard for aero-engine distributed control may be constrained by the worst-case temperature condition in the engine [9]. Currently, there exists a small but increasing pool of commercial resources with capabilities for electronic components based on silicon on insulator (SOI) operable up to 300°C and multilayer of silicon carbide (SiC) electronics operable up to 500°C [10,11]. Silicon carbide's ability to function at temperatures as high as 650°C will enable large performance range enhancements for high-temperature sensor applications [12,13,14,15]. The authors have reviewed existing high-temperature electronics components and technologies and their key packaging requirements (Table **1**). Based on this review, simple circuits that allow for analog sensing signal conditioning are possible, but the full suite of microprocessors, memory, DSPs, UARTs, and other digital components necessary for realization of a high temperature smart sensor are not yet available.

Table 1: HT Electronics Developers with Strong DEC Potential

Component Supplier	Passives	ICs	ASIC	Temp Range (°C)
Arkansas Power Electronics	X	X		<300
CISSIOD	X	X		<300
Cree	X	X		300–500
Honeywell	X	X	X	<300
Orbital Electronics	X	X	X	<300
Riedon	X			<400
TRS Technologies	X			<450
Vanguard Electronics	X			<250
Vectron International	X			250–300
xREL Semiconductor	X			230–300

As high temperature operable electronics become more broadly available, electronics packaging techniques suitable for the turbine engine environment must evolve as well. Specifically, the electronics packaging must be designed to endure high temperatures, large acceleration loads, and support non-planar installation [16].

In Situ Pressure Sensing

In situ, dynamic pressure sensing is critical to sensors to assess compressor surge and stall cell formation, margin, and operability; optical sensors and high temperature MEMS are emerging alternatives for these measurements [17]. Sporian Microsystems, Inc. has established a solid track record of successful research and development of high temperature sensors and packaging architectures for high temperature turbine engine and other advanced power systems environments. Sporian's sensor technology is based on the combination of advanced high temperature packaging and recently developed silicon carbide nitride (SiCN) based polymer derived ceramics (PDCs). SiCN based ceramics are a group of amorphous, high-temperature materials, which possess excellent mechanical and electric properties at temperatures up to 1800 ºC, which allows for the creation of devices with much higher operational temperatures than SiC or SOI based technologies [18,19,20,21,22,23,24,25].

Figure 1 shows examples of previously developed and demonstrated SiCN temperature/pressure sensor structures and the associated packaging developed for turbine engine applications at temperatures up to 1350^{o}C. The sensors and packaging have successfully completed 200 hours of Navy 'Iron Bird' turboshaft testing and 24 hours of OEM turbofan testing, both in the P3 position, as well as over 550 hours of OEM burner rig testing and 200 hours of DOE burner rig testing. The sensors are scheduled to be included in Air Force 'Small CAESAR' and NASA VIPR tests.

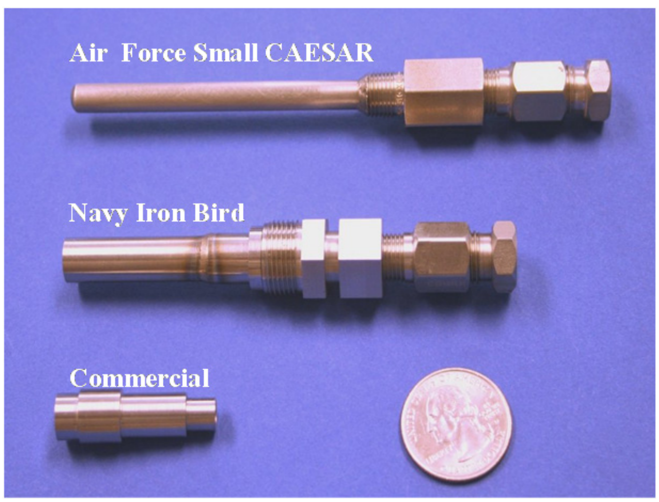

Figure 1: High Temperature, In Situ Pressure Sensors

The Sporian sensing element with the highest Technology Readiness Level (TRL) is based on a piezoresistive architecture which displays a coupled thermoresistive response. As a result, the dynamic bandwidth of the sensor is less than that specified by the Propulsion Instrumentation Working Group (PIWG) industry consortium [26]. A recent, NASA-funded effort has yielded promising results for a higher bandwidth pressure sensing architecture.

While the MEMS sensor element and packaging are relatively well developed, the associated signal conditioning and communications electronics to date are purely analog and lack many the features necessary for "smart" operation.

Smart Sensors

A smart sensor is a sensor that possesses capabilities beyond merely detecting a certain parameter and sending a raw uncompensated signal. Smart sensor functionalities can include signal conditioning, filtering, calibration, temperature compensation, linearity correction, analog-to-digital conversion, self-diagnostics, control logic, memory, and bus communication capability [27]. IEEE-1451 is a standard for a network independent connection of sensors to network controllers, including the embedding of a Transducer Electronic Data Sheet (TEDS) which allows for the connection of any transducer on the network [28].

Although network independence is a goal of IEEE-1451, data bus commonality is important to realize weight and cost reductions desired from Distributed Engine Control. Some level of commonality and standardization is also necessary to lower risk and encourage sensor and actuator vendors to enter an emerging market. Competition and economies of scale are necessary to make the new technology attractive for turbine engine manufacturers. The choice of data bus is also limited by the constraints imposed by utilization of high temperature operable electronics.

For smart sensors, firmware is a significant aspect of the operational system [29]. At present, there is an understandable lack of software/firmware development tools for emerging HT electronics. Along with the limitations of digital HT electronics, this inhibits migration of firmware developed for smart sensors utilizing traditional silicon electronics to DEC applications and drives development and support costs.

Pertinent published sources were reviewed to identify the various communications options being pursued or considered by the overall DEC community. Approximately 40 documents were reviewed, noting in detail specific communications networking technologies and standards that could be used for DEC applications. The total range included 27 different technologies or standards including various wired and wireless physical layers and higher level networking layers. For this review and list, we considered technologies that a particular document mentions as a possible option or solution, and not just the technologies that a document focuses on.

It is important to note that it is not possible to cleanly split these various technologies into categories that strictly address various networking layers. This is due to the fact that no one technology covers all required layers of a communications network. Here we use the term "layers" in the same sense as it is used in, for example, the "OSI 7 layer model" [30, 31]. Further, simply categorizing the various approaches is not strictly possible because not all communications networks can necessarily be mapped to the "OSI 7 layer model." With this said, the results of the review are presented in Table 2. The results of this review can best be summarized by saying there are a wide range of communications technologies that are potentially useful, and that are being considered for use in DEC

systems. On the positive side, a large number of qualified people are considering this question and these people appear to be giving fair consideration to all possibilities. On the negative side, no clear "winner" emerges from the published literature at this time. This means, at least from the point of view of the published literature, there is no consensus/standard/quasi-standard with respect to the communications technology to be used for DEC applications.

Table 2: Communications Technologies Addressed by Reviewed DEC Literature

Wired Interfaces	% of papers mentioning
RS232	12.5
RS485	25.0
MIL-I-1553	25.0
ARINC	12.5
CANbus	37.5
MODbus	12.5
Ethernet	25.0
Optical Ethernet	12.5
SAE-5652	12.5
ARCnetPLUS	12.5
FireWire	37.5
SAFEBus	12.5
FlexRay	25.0
SPIDER	12.5
TTP (all variants)	25.0
J1939	12.5
LVDS	12.5
Wireless Interfaces	
WiFi (IEEE 802.11)	12.5
IEEE 802.15.4	12.5
ZigBee	12.5
BlueTooth	12.5
Miscellaneous	
IEEE 1451	37.5
MicroTCA	12.5
AMC	12.5
VPX	12.5
Software Defined Radio	12.5

To supplement the literature search, the authors surveyed several relevant engine, control system, and sensor OEMs with the goal of defining:

- Preferred data bus
- Prioritized smart sensor functionality

Responses were initially solicited via email. Follow-up phone calls were made to allow for clarification and elaboration. The results of this survey are summarized in Table 3.

Table 3: Summary of Turbine Engine Supply Chain Smart Pressure Sensor Survey

Organization	Preferred Data Bus	Preferred Smart Sensor Functionality (in priority order)
Engine OEM A	Defer to DECWG	Onboard calibration, Built-In Self-Test, TEDS
Engine OEM B	RS-485 & Deterministic Ethernet. Comm-Over-Power	Onboard calibration, Built-In Self-Test, TEDS
Engine OEM C	RS-485 & Deterministic Ethernet	Onboard calibration, Built-In Self-Test, TEDS
Engine OEM D	Defer to DECWG	Defer to DECWG
Controls OEM A	Defer to Engine OEM	Defer to Engine OEM
Controls OEM B	Analog, Comm-Over-Power	No Sensor Bandwidth Penalty, Built-In Self-Test
Controls OEM C	ARINC 825	-
Controls OEM D	ARINC 825/CAN, Comm-Over-Power, NOT Multi-Drop Bus	Onboard calibration, Built-In Self-Test, TEDS
Sensor OEM A	ARINC 429, Legacy Data Bus	Onboard calibration, Built-In Self-Test, TEDS
Sensor OEM B	ARINC 429, Legacy Data Bus	Onboard calibration, Built-In Self-Test, TEDS
Sensor OEM C	ARINC 429, Legacy Data Bus	Onboard calibration, Built-In Self-Test, TEDS

The authors also attended the DECWG Requirements Review in Cleveland on March 1, 2012. The weaknesses of several candidate data busses (lack of EMI protection, encryption for data security, licensing fees driving costs) were discussed. Though there was no apparent strong statement of endorsement, there was some apparent DECWG preference/endorsement of LIN bus and deterministic Ethernet. It was emphasized that DECWG would only support open standards to keep costs down by avoiding licensing fees. Therefore, protocols such as proprietary TTP, TTE and AFDX are apparently excluded from consideration. Since that Requirements Review meeting, the DECWG preference for LIN bus appears to have evolved to Engine Area Distributed Interconnect Network (EADIN) bus [32].

The authors' approach for dealing with the constraints of HT electronics and uncertainties of the emerging DEC application is to utilize a hybrid approach to smart sensor implementation. HT electronics would be used for critical analog signal conditioning functions such as signal amplification. Digital smart sensor functionality, such as data bus interface, built-in self-test and TEDS, would be implemented through rugged, miniaturized packaging of traditional silicon electronics for application farther away from the engine core (Figure 2).

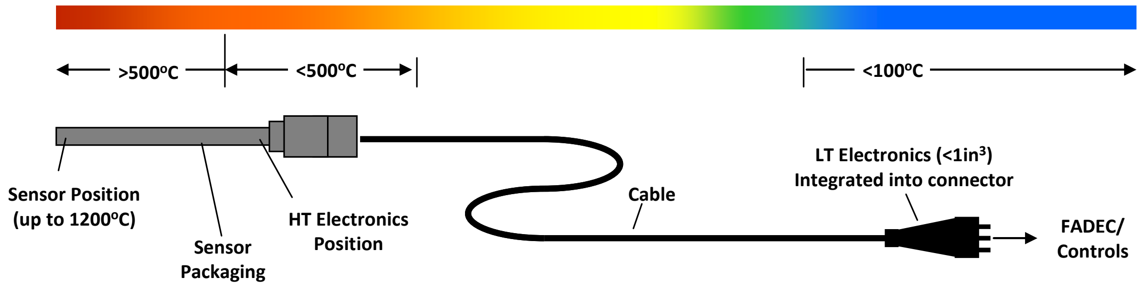

Figure 2: Smart Sensor utilizing Hybrid HT- and LT-Electronics

First generation prototypes have shown promising performance. A room temperature, digital 'smart' sensor prototype board is shown in Figure 3. This board is a 'stretch' version to allow for easy circuit debugging; the final version will be less than 1 in^3.

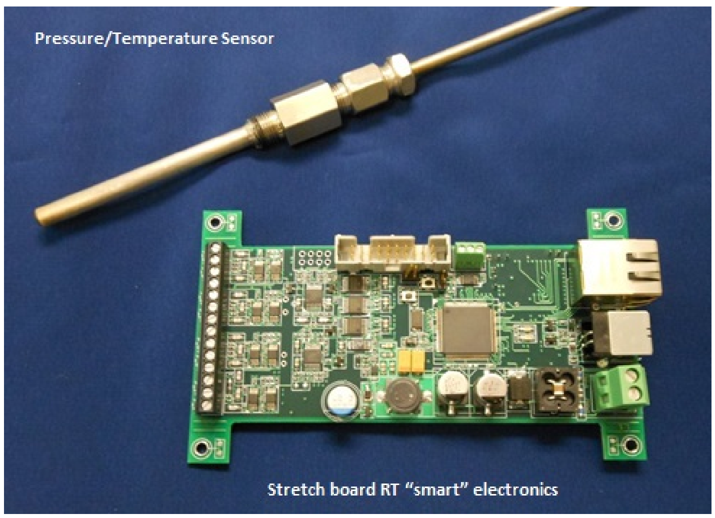

Figure 3: RT Electronics

Electronics Packaging

Traditional electronics packaging does not contemplate the elevated temperatures, acceleration loads, and constrained, non-planar application of a DEC environment. Therefore, an adaptable, conformal, high-temperature packaging and installation methodology is needed to support emerging high temperature electronics technology [33,34,35].

The key issue is that, as these components leverage typical planar wafer fabrication process flows, the resulting components are in discrete "chip" or "die" formats that cannot be realized in a non-planar form and cannot be applied to conformal surfaces without additional packaging [36,37,38]. Further, as these new high temperature processes are vastly less advanced than traditional semiconductor processes, currently only functionally simple elements (MOSFETs, diodes, SSI) have been realized. As a result, differing processes are often required to realize different components, which means combining such components into basic sensing and signal conditioning circuits typically requires multi-chip (discrete component) packaging integration. Such multi-chip module packaging for ultra-high temperature electronics is a relatively unexplored area,

and conformally interfacing such approaches with non-planar engine components is an even more novel problem.

The technical approach for this effort has been to utilize proven packaging technologies combined with new high temperature materials to create conformal multi-component modules and realize a generic and adaptable packaging methodology that can be applied to non-planar aerospace structures. The first step is a specially fabricated, non-planar substrate. The substrate is patterned with metallization to form both electrical interconnects, routing and potentially transmitter components including low profile antennae, resistors and/or capacitors. Electronic components would be attached to this substrate via either flip-chip bonding or high temperature die attach and necessary additional interconnects formed using high temperature wire or ribbon bonding. The discrete components and substrate would then be coated or encapsulated with an electrically insulating layer to protect the electronics from the harsh environment and increase the overall durability, with the exception of any portions (e.g. pressure sensing elements) that may require exposure to the environment. This "conformal package" would be bonded to the target location via a ductile intermediate layer.

Each step in this packaging process is being systematically developed by the authors to yield a packaging methodology that meets or exceeds the environmental constraints of current HT electronics components. Results from this effort are summarized in Table 4.

Conclusions

Continuing improvements in turbine engine performance will require a technology convergence of high temperature sensing, high temperature electronics, high temperature packaging, and advanced control systems.

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Table 4: Packaging Process Development

Test Item	T (°C)	Duration/G	Results
5-type ceramic substrate	600°C	100hr, multicycle	No degradation on flexural strength, Dimensionally stable
5-type ceramic substrate	850°C	Single sweep	Low dielectric dissipation under 500°C
Conformal Au metallization	600°C	100hr, multicycle	Reliable electrical continuity, and adhesion
Conformal Pt metallization	600°C	100hr, multicycle	Reliable electrical continuity and adhesion
Multilayer conformal substrate	600°C	100hr, multicycle	Good geometrical and dimensional stability
Multilayer Au metallization	600°C	100hr, multicycle	Reliable electrical continuity and adhesion
Multilayer Pt metallization	600°C	100hr, multicycle	Reliable electrical continuity and adhesion
Multilayer with via/window	600°C	100hr, multicycle	Reliable electrical continuity and adhesion
Die-attach cements	1000°C	>20hr, Multicycle	Shear strength can survive 56 kG
Die-attach	600°C	100hr, multicycle	No degradation on shear strength
Au wire bonding on Au metallization	600°C	100hr, multicycle	Reliable electrical continuity, Limited deformation/softening
Au flip-chip bonding on Au metallization	600°C	100hr, multicycle	Reliable electrical continuity, Reliable mechanical attachment
Au wire bonding on Pt metallization	600°C	100hr, multicycle	Reliable electrical continuity, Limited deformation/softening
Au flip-chip bonding on Pt metallization	600°C	100hr, multicycle	Reliable electrical continuity, Reliable mechanical attachment
Potting cements	1000°C	>20hr, multicycle	No degradation of performance
Potting cements	600°C	100hr, multicycle	Shear strength can survive 56 kG
Prototype w/ potting	600°C	100hr, 10-cycle	Reliable electrical continuity
Thermal spray coat	700°C	30min	Reliable electrical continuity and adhesion
Coating glazes	600°C	100hr, multicycle	No degradation on materials
Prototype w/ coating	600°C	100hr, multicycle	Reliable electrical continuity
Installation: Cements	600°C	100hr, multicycle	Die shear samples survived 30 kG
Installation: Au-paste	600°C	100hr, multicycle	Die shear samples survived 56 kG
Install: C-M Brazing	600°C	100hr, multicycle	Die shear samples survived 30 kG
Install: M-M Brazing	800°C	100hr, multicycle	Die shear samples survived 900 kG
Bonding/installation	Room	8.3 kG	Au-paste and brazing joints survived
Bonding/installation	300°C	4.6 kG	Au-paste and brazing joints survived
Bonding/installation	500°C	1.3 kG	Au-paste and brazing joints survived
Complete prototypes	Room	17 kG	Reliable electronics packaging/installation
Complete prototypes	600°C	1 kG	Reliable electronics packaging/installation
Metallization	800°C	100 hr, multicycle	No apparent degradation
Die-attach	800°C	100 hr, multicycle	No apparent degradation
Wire bond, flip-chip	800°C	100 hr, multicycle	Survived
Substrate materials	800°C	100 hr, multicycle	Decreased strength
Prototype packaging	300°C	13 kG	Reliable high-T high-G performance
Functional prototype	275°C		Reliable electrical performance

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16 May 2013

Instrumentation - Aerospace Applications

Intelligent Turbine Engine Controls

Session E4 - Roxy

Advanced Sensor and Packaging Technologies for Intelligent Adaptive Engine Controls

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Kevin F. Harsh[1], Yiping Liu[1], Alireza R. Behbahani[2]

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59th International Instrumentation, Symposium – Cleveland, OH

Presenter

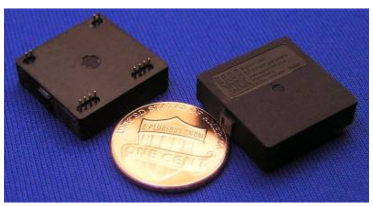
- Mike Usrey
  - Vice President at Sporian Microsystems, Inc.
  - Ph.D. Industrial Engineering-University of Minnesota
  - Professional Engineer / Certified in Production & Inventory Mgmt
  - Previously:
    - Project Manager – Honeywell
    - CTO – EnergyWindow
    - CEO – Protocol Communications
    - Faculty – University of Colorado

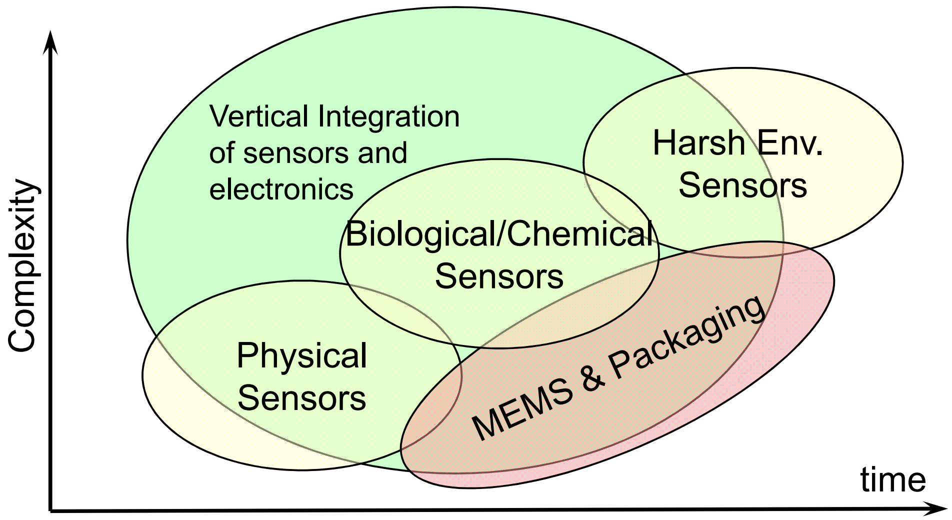
Outline

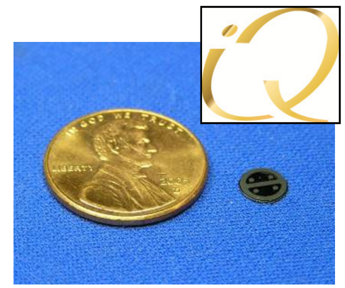
- About Sporian
- Motivation
- Smart Pressure Sensor Concept
- Analog Pressure Sensor
- High Temperature Electronics
- High Temperature, Conformal Packaging
- Results to Date

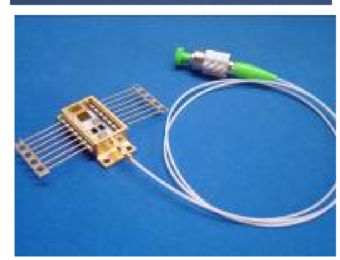
About Sporian

- **4 primary development efforts at Sporian:**
  - Physical sensors – shock, humidity, temperature, etc.
  - Photonic-based chem/bio-sensors.
  - Harsh Environment/High Temperature (1000-1400^{o}C) MEMS packaging & sensors
  - Systems integration (signal processing, logging, storage, communications)

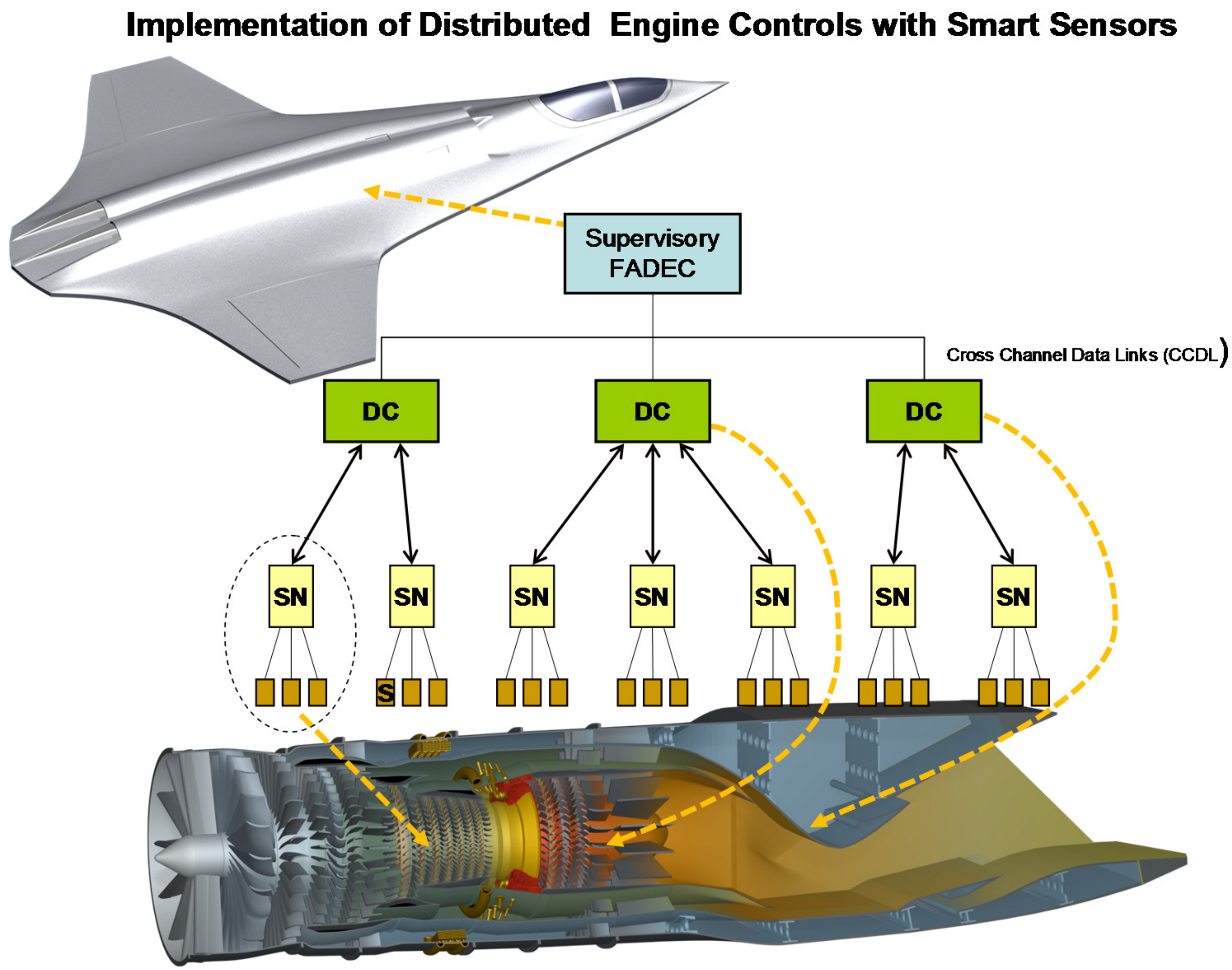






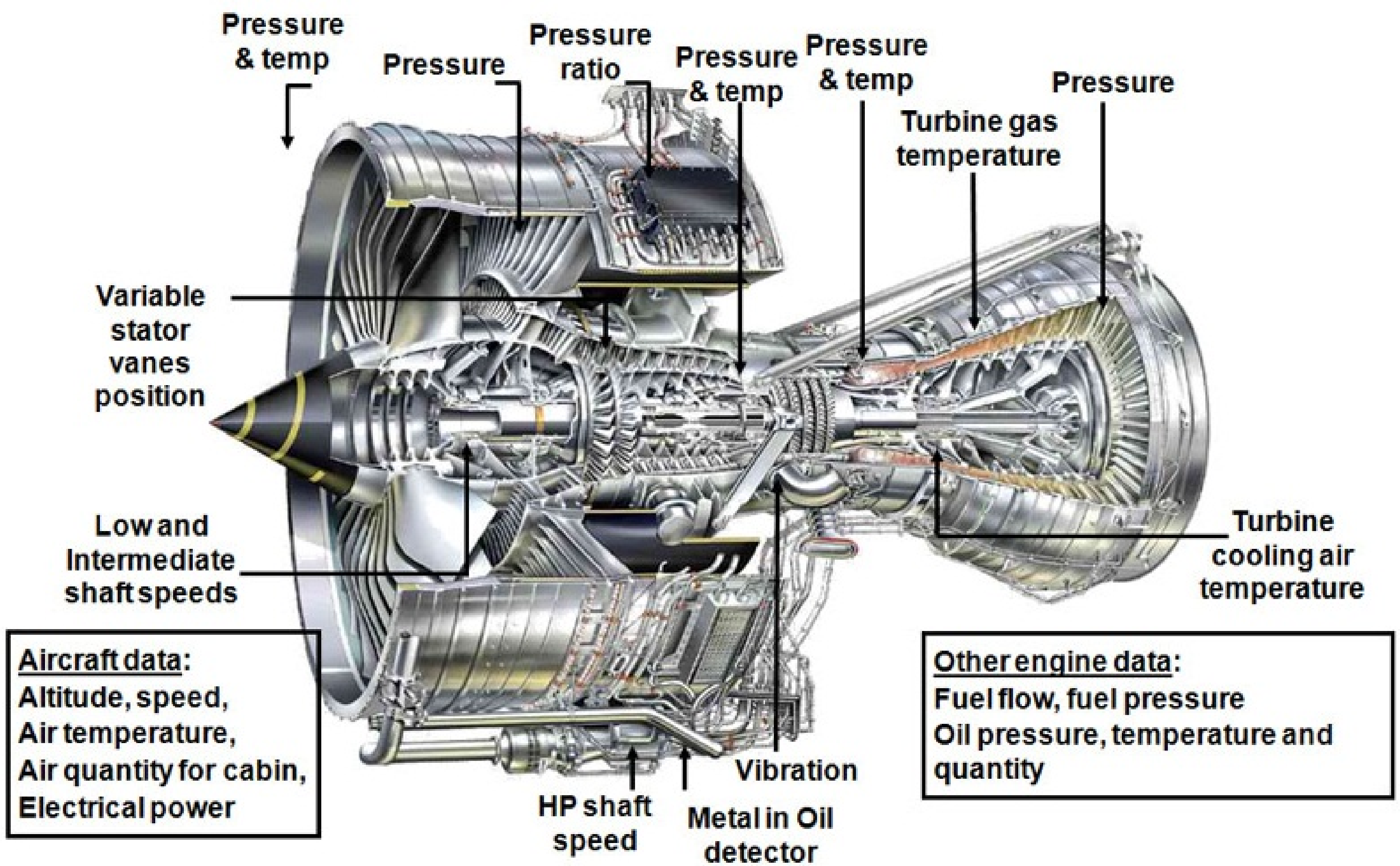


Motivation



Implementation of Distributed Engine Controls with Smart Sensors
Supervisory FADEC
Cross Channel Data Links (CCDL)
DC
DC
DC
SN
SN
SN
SN
SN
SN
SN
S

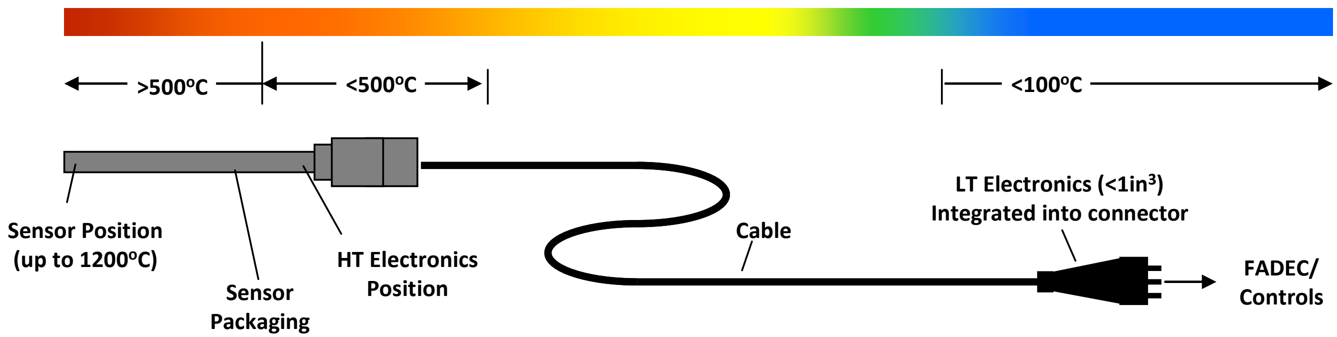
Motivation

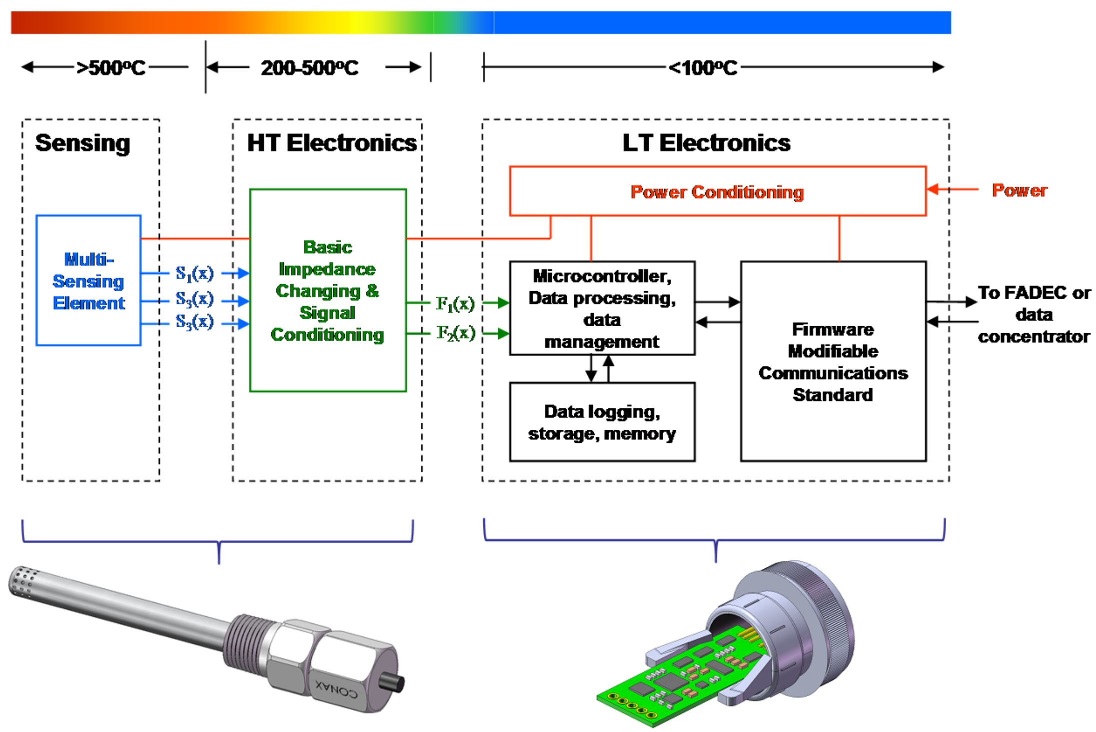

Pressure & temp
Pressure
Pressure ratio
Pressure & temp
Pressure & temp
Pressure
Turbine gas temperature
Variable stator vanes position
Low and Intermediate shaft speeds
Turbine cooling air temperature
Aircraft data:
Altitude, speed,
Air temperature,
Air quantity for cabin,
Electrical power
Other engine data:
Fuel flow, fuel pressure
Oil pressure, temperature and quantity
HP shaft speed
Metal in Oil detector
Vibration

Motivation

- ***Need/Challenge** :There is a growing demand for smart, high-temperature pressure sensors, signal conditioning electronics, and packaging in extreme environments providing information on engine conditions at the harshest environments.*
  - Able to communicate over a data bus to FADEC/controller - support distributed engine control
  - Compressor discharge pressures (0 to 700 psi) and temperatures (800^{o}C- 1000^{o}C) +/- .75% or +/- 0.5 psi accuracy
  - Reduced size and weight
  - Smart sensor features – conditioned output, BIT status indicators, digital interface
  - Portions of electronics and packaging at elevated temperatures
- ***Approach:*** Leverage Sporian's previously developed and demonstrated high temperature pressure sensor technology and advance the sensor electronics and packaging into a "smart" form suitable for engine control applications/use.

Smart Pressure Sensor Concept





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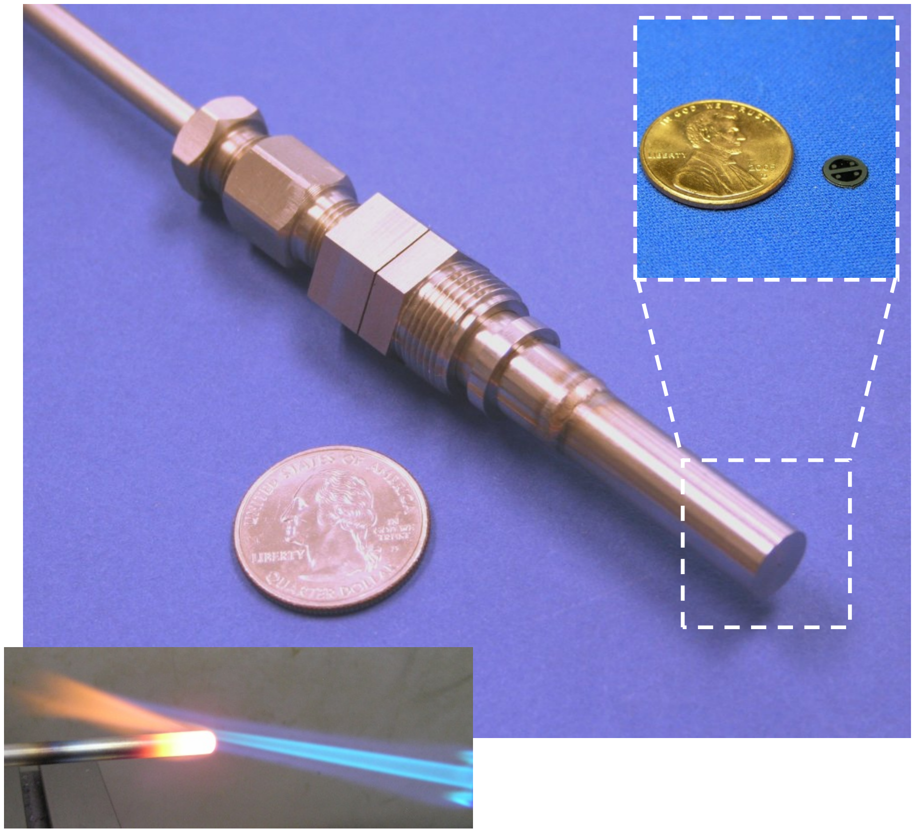
Analog Pressure Sensor

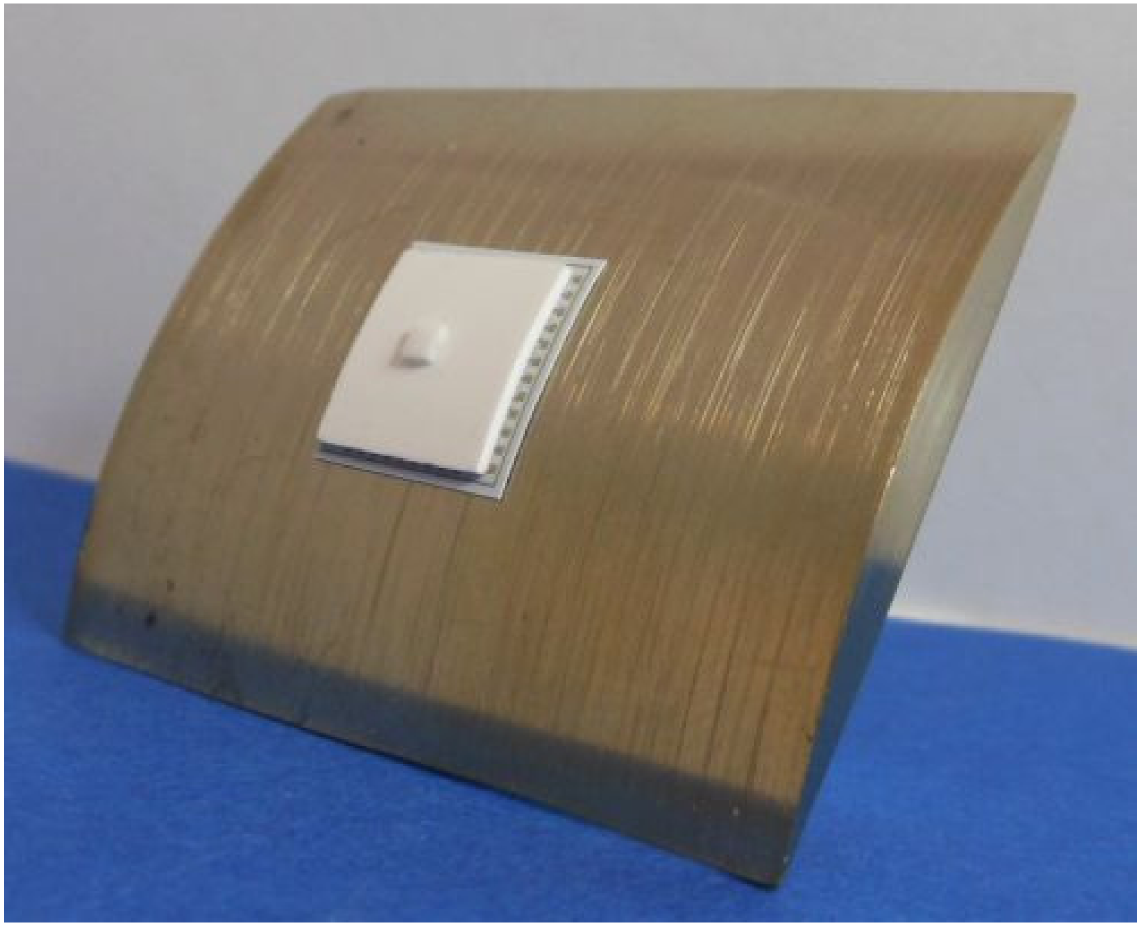


Characteristic	Performance
Pressure Range (psi)	Atm-1000
Operation Temperature (C)	RT-1350
Frequency (khz)	1
Length (in.)	2-10
Diameter (in)	≥.25
Sensitivity/Combined Uncertainties	≤ 1% FS

High Temperature Electronics

Component Supplier	Passives	ICs	ASIC	Temp Range (°C)
Arkansas Power Electronics	X	X		<300
CISSIOD	X	X		<300
Cree	X	X		300–500
Honeywell	X	X	X	<300
Orbital Electronics	X	X	X	<300
Riedon	X			<400
TRS Technologies	X			<450
Vanguard Electronics	X			<250
Vectron International	X			250–300
xREL Semiconductor	X			230–300

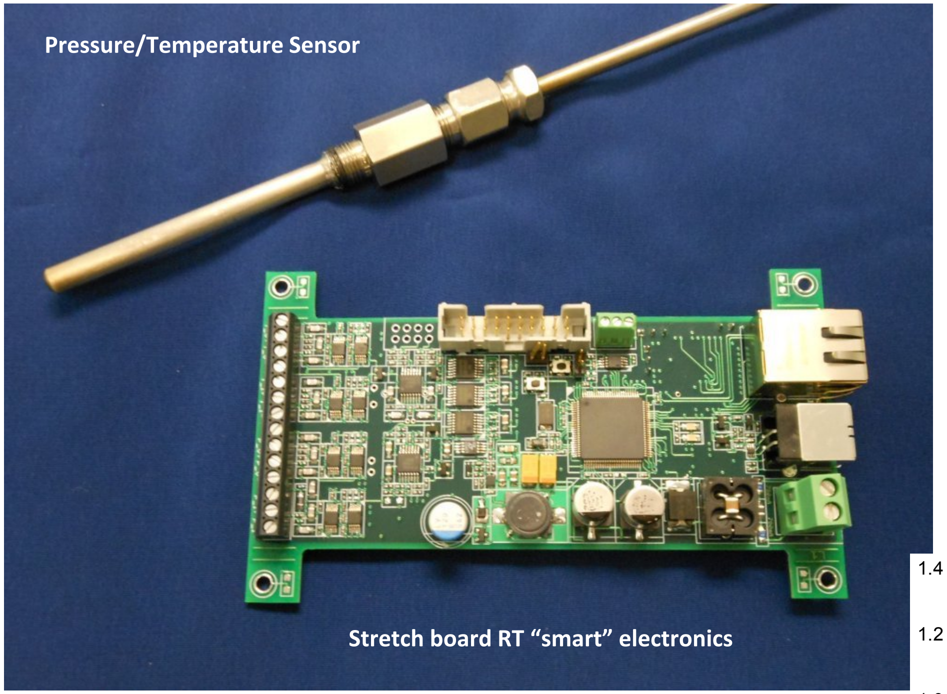
High Temperature, Conformal Packaging



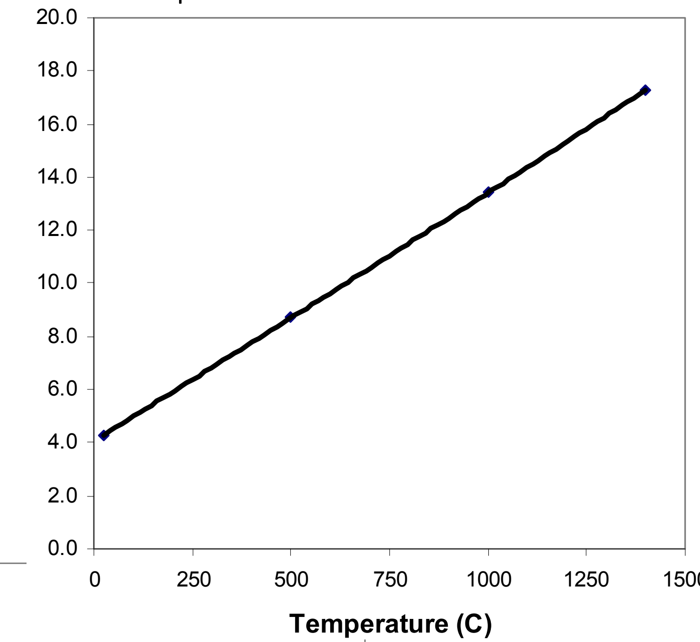
High Temperature, Conformal Packaging

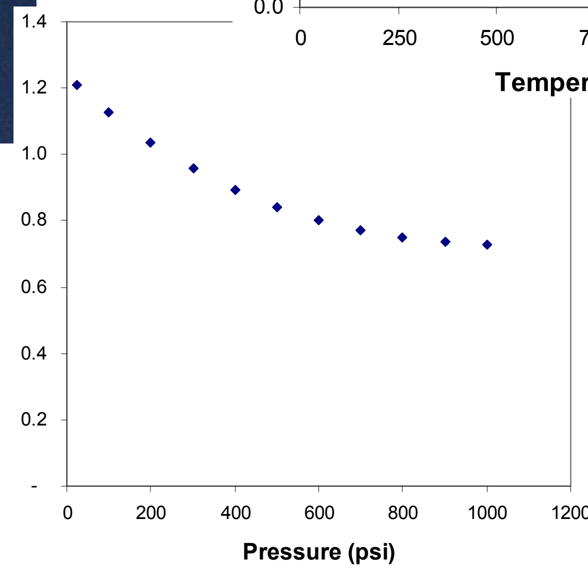
Test Item	Temp.	Duration	Results
Substrate materials	600 °C	100hr, multi-cycle	No degradation on flexural strength Dimensionally stabile
Substrate materials	850 °C	Single sweep	Low dielectric dissipation under 500°C
Conformal gold metallization	600 °C	100hr, multi-cycle	Reliable electrical continuity Stable adhesion to substrate
Conformal platinum metallization	600 °C	100hr, multi-cycle	Reliable electrical continuity Stable adhesion to substrate
Multilayer conformal substrate	600 °C	100hr, multi-cycle	Good geometrical and dimensional stability
Multilayer gold metallization	600 °C	100hr, multi-cycle	Reliable electrical continuity Stable adhesion to substrate
Multilayer platinum metallization	600 °C	100hr, multi-cycle	Reliable electrical continuity Stable adhesion to substrate
Die attach cements	1000°C	>20hr, Multi-cycle	Shear strength can survive 56 kG
Die attach	600 °C	100hr, multi-cycle	No degradation on shear strength
Au wire and flip chip bonding on Au metallization	600 °C	100hr, multi-cycle	Reliable electrical continuity Limited deformation/softening
Au wire bonding on Pt metallization	600 °C	100hr, multi-cycle	Reliable electrical continuity Limited deformation/softening
Au flip-chip bonding on Pt metallization	600 °C	100hr, multi-cycle	Reliable electrical continuity Reliable mechanical attachment
Potting cements	1000°C	>20hr, multi-cycle	No degradation on performances
Potting cements	600°C	100hr, multi-cycle	Shear strength can survive 56 kG
Potting glazes	600 °C	100hr, multi-cycle	No degradation on materials
Prototype w/ coating	600 °C	100hr, Multi-cycle	Reliable electrical continuity
Installation: Cements/Au-Paste	600 °C	100hr, multi-cycle	Shear strength can survive 56 kG
Installation: Brazing	600 °C	100hr, multi-cycle	Shear strength can survive 56 kG
Complete prototypes	Coupled 600 °C and 1000G Coupled 300 °C and 13000G		Packaging and installation survived Reliable electrical continuity

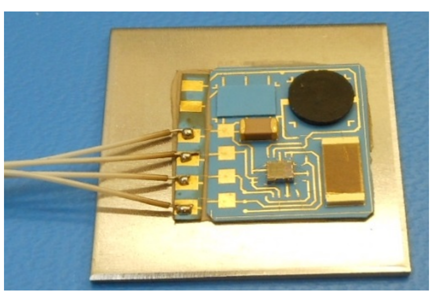
Results to Date



Measured Sensor Output







High Temperature electronics

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